

Ballistic and Diffuse Electron Transport in Nanocontacts of MagneticsR.G. Gatiyatov,^{1, a)} V.N. Lisin, and A.A. Bukharaev*Zavoisky Physical-Technical Institute RAS, 420029 Kazan,
Russia*

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The transition from the ballistic electron transport to the diffuse one is experimentally observed in the study of the magnetic phase transition in Ni nanocontacts with different sizes. It is shown that the voltage U_C needed for Joule heating of the near-contact region to the critical temperature does not depend on the contact size only in the diffuse mode. For the ballistic contact it increases with decrease in the nanocontact size. The reduction of the transport electron mean free path due to heating of NCs may result in change of the electron transport mode from ballistic to diffusive one.

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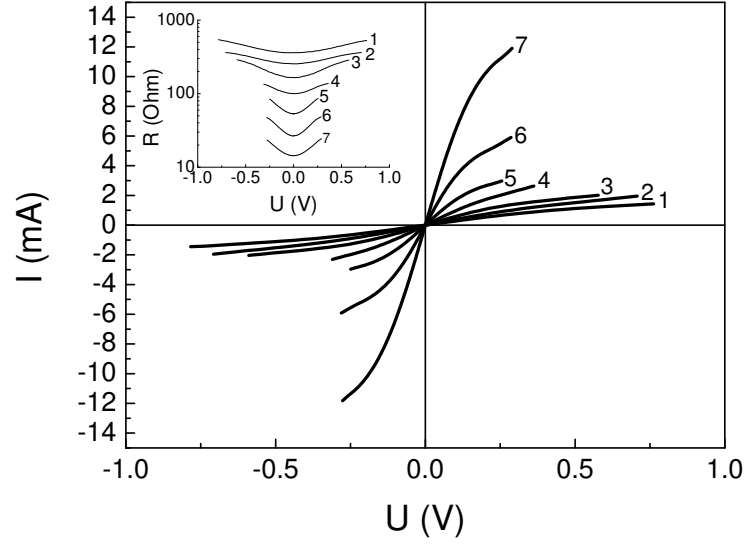
^{a)}Electronic mail: Ruslan.Gatiyatov@gmail.com

In modern micro- and nanoelectronics devices, as a rule, the diffuse electron transport is implemented when the transport mean free path l_{tr} is less than the characteristic size of a device d . Further, with decrease in d the ballistic electron transport becomes a typical one ($d \ll l_{tr}$) when electrons pass through a nanoobject without collisions. In metal nanocontacts (NCs) the condition $d \ll l_{tr}$ can hold at room and higher temperatures¹. It was recently concluded upon studying the passage of electrons through NCs of magnetic metals^{1,2} that not only in the diffuse NCs but also in the ballistic ones it is necessary to take into account Joule heating of the near-contact region. Moreover, the temperature of the ballistic NCs can reach the critical value at which the magnetic phase transition occurs. We established earlier¹ that the external voltage value U_C necessary for heating the ballistic NCs to the phase transition point T_C increases with reduction of the NC diameter d while in Ref.² it was concluded that U_C does not depend on d . In our opinion, it is interesting to clarify the origin of this contradiction since the study of the features of heating of NCs and the neighboring regions by the current is one of the topical problems of studying magnetic NCs. In particular, this is connected with the implementation of the spin transfer torque effect in such structures^{3,4}.

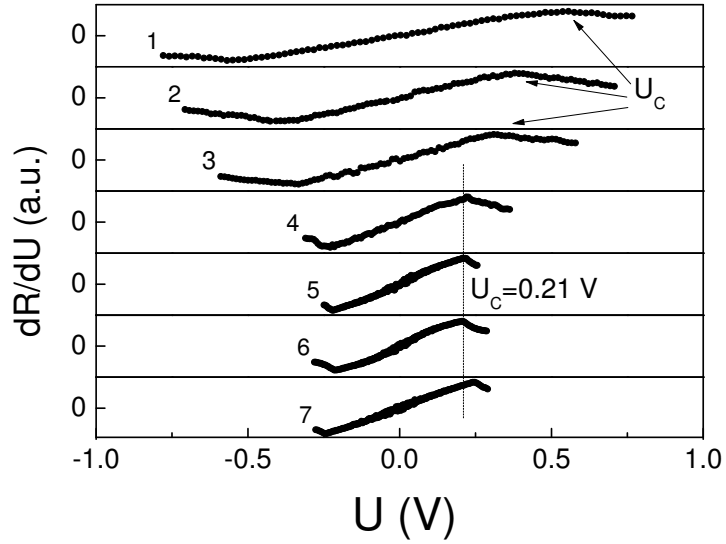
To clarify the origin of such a noticeable distinction between the conclusions made in Ref.^{1,2}, in this work the electron transport in Ni NCs is studied in a wider range of the NC sizes than in Ref.¹ (range of the resistances at zero voltage $R_0 = 13 \div 400$ Ohm which in our estimates corresponds to the diameter values $d = 1.5 \div 12$ nm).

The measurements were performed at room temperature in a wide range of voltages applied to NCs. Ni NCs were formed in solution using an electrochemical method described in Ref.¹ in detail. The conductance was measured by the four-contact method with two digital multimeters, Agilent 34410a. Current-voltage (I-V) characteristics of NCs were recorded by applying a single triangular voltage pulse to the circuit. The pulse frequency varied from 10 to 100 Hz. Ni NCs were formed in the nickel sulfate solution $0.25 \text{ NiSO}_4 + 0.5 \text{ H}_3\text{BO}_3$ (working voltage $1 \div 1.4$ V) in the gap between two Ni microwires fixed on a nonconducting substrate. I-V curves were recorded in the bath with bidistilled water, which has the conductivity much smaller than the NC conductivity.

Figure1 shows the I-V curves (Fig.1a) and dependences of the resistance $R = U/I$ (in the inset) and voltage derivative of resistance dR/dU (Fig.1b) of Ni NCs with different diameters (different resistances R_0 at $U = 0$ V) on the value of the applied potential difference U . One



(a)



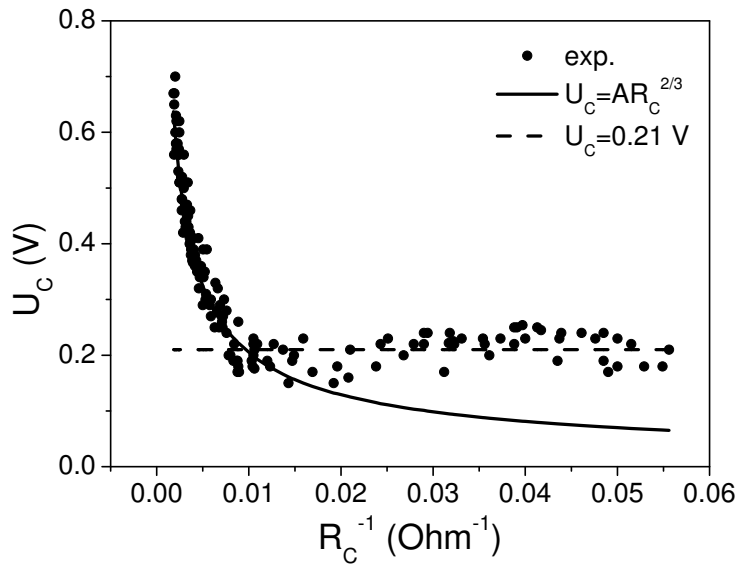
(b)

FIG. 1. I-V curves (a) and dependences of the resistance (inset) and voltage derivative of resistance on the applied potential difference (b) for Ni NC with different sizes. Numbers correspond to the following values of the NC resistance at zero potential difference: 1 – 363 Ohm, 2 – 254 Ohm, 3 – 165 Ohm, 4 – 100 Ohm, 5 – 53 Ohm, 6 – 26 Ohm, 7 – 14 Ohm.

can see in Fig.1a that the I-V curves are nonlinear. With increase in the applied voltage the NC resistance increases. The voltage derivative of resistance dR/dU was found by the

numerical differentiation of the experimental dependence $R(U)$. There are a maximum at $U = U_C$ and a symmetrically located minimum $U = -U_C$ in the dependences of the voltage derivative of resistance (Fig.1b). It is seen that with increase in the Ni NC size (reduction of the resistance $R_C = R(U_C)$) the U_C value decreases and reaches a plateau for $R_C < 100$ Ohm.

Figure 2 shows the experimental dependence of the U_C value on R_C^{-1} . The U_C value nonmonotonically declines with increase in R_C^{-1} (increase in the contact size), and for $R_C < 100$ Ohm reaches a plateau and becomes $U_C = 0.21 \pm 0.03$ V.



(a)

FIG. 2. Dependence of the voltage U_C necessary for heating NC to the critical temperature on the NC resistance at this voltage (solid line, the dependence calculated according to equation (1); dashed line corresponds to $U_C = 0.21$ V).

According to¹, the nonlinearity of the I-V curves is due to heating of NC by a current running through it. It was shown that the maximum (minimum) in the $dR/dU(U)$ dependences (Fig.1b) is due to the local phase transition from the ferromagnetic to the paramagnetic state of the contact region because of heating above the Curie temperature¹, which for Ni is $T_C = 631$ K⁵.

We studied Ni NCs with $R_C > 100$ Ohm in Ref.¹. It was shown that in such NCs the ballistic electron transport was implemented. The dependence of the U_C value on R_C for

this region is described by the expression:

$$U_C = A \cdot R_C^{\frac{2}{3}}, \quad (1)$$

where $A = (0.95 \pm 0.12) \cdot 10^{-2} \text{ V/Ohm}^{\frac{2}{3}}$. Figure 2 shows the dependence of U_C on R_C^{-1} (solid line according to (1)).

It should be emphasized that in the region $R_C < 100 \text{ Ohm}$ the U_C value no longer depends on the contact size within the scatter of the experimental values (Fig.2). It is known that in diffuse contacts the voltage value needed for heating to the same temperature does not depend on the contact size⁶, and is related to the temperature in the contact center by the following relation:

$$U_C^2 = 8 \int_{T_0}^{T_C} \lambda \rho dT, \quad (2)$$

where λ is the coefficient of thermal conductivity, ρ is the resistivity.

By numerically integrating (2), using tabular data for the temperature dependence of the coefficient of thermal conductivity and resistivity of Ni⁷, we find that $U_C = 0.17 \text{ Ohm}$. The calculated value is somewhat below the average experimental value $U_C = 0.21 \text{ V}$ but is within the scatter of the experimental data. This allows us to state that for Ni NC with $R_C < 100 \text{ Ohm}$ the diffuse electron transport is implemented.

On the basis of the above one can conclude that the experimental data (Fig.2) indicate the transition from the ballistic ($d \ll l_{tr}(T_C)$) electron transport in Ni NC to the diffuse ($d > l_{tr}(T_C)$) one at the temperature of the magnetic phase transition T_C . In the ballistic mode U_C depends on the NC size which contradicts the results of Ref.².

In our opinion, this is due to the fact that the sizes of the studied Au/CoS₂ and Au/Ho contacts in Ref.² were too large for the implementation of the ballistic electron transport in NCs heated to the temperature of the phase transition. The estimates of l_{tr} in Ref.² were given for the initial temperature $T_0 = 4.2 \text{ K}$. The increase in the resistance with increase in the voltage indicates the reduction of l_{tr} . This can lead to the transition from the ballistic electron transport ($l_{tr}(T_0) \gg d$) to the diffuse ($l_{tr}(T_C) < d$) one. Using the tabular resistivity value $\rho(T_N) = 52 \cdot 10^{-8} \text{ Ohm}\cdot\text{m}$ for Ho [Ref.⁵] at the Neel temperature T_N and assuming $\rho \cdot l_{tr} = 10^{-15} \text{ Ohm}\cdot\text{m}^2$ the same as in Ref.², we obtain $l_{tr}(T_N) = 1.9 \text{ nm}$. The estimated $l_{tr}(T_N)$ value is less than the contact sizes in Ref.² therefore in these contacts

the diffuse electron transport is implemented. Analogous estimates can be made for the Au/CoS₂ contact.

Thus, one can consider that in Ref.² the electron transport in NCs heated to the temperature of the magnetic transition was rather diffuse than ballistic, since the l_{tr} values were overestimated. This is also confirmed by the observation that the voltage value U_C does not depend on the contact size which agrees well with the ideas about the diffuse electron transport in similar structures.

The growth in U_C with decrease in the contact diameter can be qualitatively understood as follows. For ballistic NCs, the size of the region where heat is released does not depend on the contact size⁸. The temperature of the heated region is determined by the released power $P = U^2/R$. Its resistance R increases with decrease in the contact diameter. To keep the NC temperature constant, it is necessary for the released power to be constant as well and, consequently, it is necessary to increase the voltage U .

It is interesting to note that value of the transport electron mean free path at the temperature of the phase transition can be estimated from the experimental dependence of U_C on R_C^{-1} . The NC resistance can be expressed by means of the Wexler interpolation formula⁹ via the Maxwell resistance R_M for the diffuse contact and Sharvin resistance R_{Sh} , describing the NC resistance in the ballistic mode:

$$R_C = \gamma_W R_M + R_{Sh} = \frac{\gamma_W \rho(T_C)}{d} + \frac{\gamma_{Sh} C}{d^2}, \quad (3)$$

where ρ is the resistivity, d is the NC diameter, $C = \rho \cdot l_{tr}$ is the coefficient, which is determined by the properties of the Fermi surface and does not depend on the dissipation mechanism, γ_W is the correction coefficient⁹, $\gamma_{Sh} = 16/3\pi$. By equalizing $\gamma_W R_M$ and R_{Sh} , we find that in the transition point:

$$d = \gamma_{Sh} l_{tr} / \gamma_W. \quad (4)$$

The value of the contact resistance corresponding to the transition from the ballistic electron transport to the diffuse one is found from the intersection of the two curves (Fig.2), describing the ballistic and diffuse contacts, which is $R_C^* = 100$ Ohm. By substituting R_C^* and (4) in (3), we find $l_{tr}(T_C) = 1.8$ nm, $d = 4.1$ nm and $C = \rho \cdot l_{tr} = 5 \cdot 10^{-16}$ Ohm·m². The following parameter values: $\gamma_W = 0.75$ [Ref.⁹], $\rho(T_C) = 27.8 \cdot 10^{-8}$ Ohm·m [Ref.⁷] were used in calculations.

Thus, it was demonstrated that it is important to take into account the reduction of the transport electron mean free path due to heating of NCs upon studying the mode of the electron transport through NCs. This reduction of the electron mean free path can lead to the transition from the ballistic electron transport to the diffuse one. As a result, the voltage value needed for heating of NCs to the critical temperature no longer depends on the NC size.

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